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XIX.

MOUNTAIN SURVEYING.

By Professor E. C. Pickering.

Read, Jan. 11, 1876.

The difficulties and expense of a topographical survey are always very great; and this is particularly the case in a mountainous country, owing to the short horizontal interval between the contours, their irregularity, and the labor involved in reaching the more elevated portions. The objections to the usual trigonometrical methods are, that the theodolite, or transit, needed to measure the angles, is heavy, liable to injury when carried over a rough country, and the time required to measure each angle is considerable. The labor and cost of measuring a base-line are also very great. Moreover, the accuracy attained is much greater than is ordinarily needed; since, as the land is commonly of little value, there is no need of determining positions with more accuracy than they can be shown on a map. If the tract of country is large, a scale greater than $\frac{1}{100000}$, or $\frac{1}{50000}$, is rarely used; and, owing to the unequal expansion and contraction of the paper, long distances could not be measured with accuracy on such a map much nearer than within fifty to one hundred metres. Another objection to the trigonometrical method is, that the work must be carried on continuously from one base to the other; and no positions can be determined except by connection with a base through a series of triangles. If, however, the latitudes and longitudes of several points are ascertained, each of them may be used as a centre from which the form of the surrounding country may be determined; and an error in one will in no way affect the position of the others. The problem proposed, therefore, was to devise some instrument which should give approximately the distance and elevation of a mountain summit or other object, and which at the same time should be light and not easily injured. With such an instrument, an exploring party, whenever they camped at a point commanding an extensive view, could, during the night, determine their latitude and longitude, and, during the day, locate all prominent visible objects.

To measure small distances, the method of the stadia and telemeter gives excellent results, but is open to the objection that an assistant is needed, who must carry a graduated pole to each point whose distance is to be determined. This method also is only applicable to short distances; as beyond five hundred, or at most a thousand metres, the pole appears so small, that its apparent length cannot be determined with accuracy.

These difficulties are, in a great measure, avoided in the following instrument. A good traveller's telescope, or spy-glass, is mounted firmly on a tripod, and a spider-line micrometer or scale of equal parts is inserted in its eye-piece. In front of the object-glass is fastened a piece of plane-glass, which may be set at any desired angle, and clamped firmly. The angle may be roughly measured by a small circle divided into degrees. The whole is free to turn around the axis of the telescope. To measure the distance of any object, *D*, Fig. 1, the angular magnitude of the divisions of the scale in the eye-piece, is first determined by the usual methods. The telescope is then mounted at *A*, and directed towards *D*, taking care to select for it some sharply defined object, as a rocky crag, the trunk of a tree, or the edge of a snow-bank. Select a second object, *C*, nearly at right angles to *D*, and turn the glass in front of the telescope until the reflection of *C* in its front surface shall be in the field at the same time as the image of *D* transmitted through the glass. Measure accurately the interval between the two images with the micrometer. Next measure off a distance *AB* from *A* towards *C* of one or two hundred metres, and place the telescope at *B*. Again measuring the interval between the two images, taking care not to disturb the mirror, a result will be obtained which will differ from the previous measurement by the angle *ADB*. From this triangle we deduce $DB = AB\frac{\sin A}{\sin D} = AB \sin A \frac{206265}{ds}$, in which d is the difference in the scale-readings, and s the magnitude of each division in seconds. *A* should be taken nearly 90°; in which case sin *A* will very nearly equal unity. Its value may be found with sufficient precision with the divided circle attached to the mirror, or by a plane-table. The greatest accuracy will be attained when *AB* has

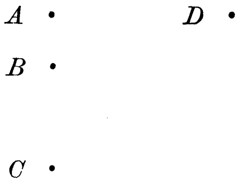

Fig. 1.

such a value as to make the angle at *D* nearly twice the diameter of the field. To determine the degree of accuracy attainable with such an instrument, suppose the diameter of the field of view 1°, and that an error of .1′ or 6″ is committed in the measurement, — a large error, considering how accurately seconds are determined with the spider-line micrometer in astronomical work. Suppose, again, that the object *D* is ten thousand metres distant, or 6.21 miles, and that *AB* is taken equal to two hundred metres: the error in question would then equal only fourteen metres, or forty-six feet, — a quantity quite insensible on the scale proposed above. Again: if the object is fifty or a hundred kilometres distant, it is only necessary to increase *AB* in the same proportion, and we shall still be able to measure the distance of *D* with the same proportionate accuracy, without yet using a base of inconvenient length. In this way, if the country is dangerous, the observer may measure the distance of all visible objects without going far from camp. Comparing this instrument with the stadia, we see that it has the advantage that it is not necessary to send a man to the point to be measured, and that the accuracy is the same as if he could carry a pole one or two hundred metres in length.

Three methods have been employed for the determination of heights. First, by the barometer. But this involves a visit to every point to be measured, and, at the best, is very inaccurate. Observations in Switzerland and California have shown, that with the best barometers, after applying all the known corrections, and even if each observation is the mean of thirty, taken once a day for a month at the same hour, at both the upper and lower stations, there still remains an uncertain error, amounting sometimes to two per cent of the whole height. How much greater, then, must be the error of a single reading, often made without simultaneous observations below, and with the defects of an aneroid added to the other errors! The most accurate method of determining a height is by levelling; but the labor and expense of this are too great to allow its frequent use in mountainous countries. The third method is that of zenith distances, which is largely used in the Coast Survey for determining heights. The altitude is here observed by a large vertical circle, which must be read with the utmost precision, since the angle, if the object is distant, rarely exceeds two or three degrees. It is claimed that at least an equal degree of accuracy may be attained by the instrument described below, while the expense of a graduated circle and delicate mounting is wholly avoided. The principle employed is that of the zenith telescope, so largely employed in determining the latitude. It consists simply of the telescope, described above, turned around its axis 90°, and a delicate level screwed firmly to its tube. To make sure that the telescope is turned by precisely the right amount, it is well to have a second level at right angles to this to render the threads of the micrometer exactly horizontal. The size of the divisions of the level and of the micrometer must be previously determined; their relative value being most easily found by directing the telescope towards any distant object, and slightly inclining it, so that the bubble shall occupy various positions in the tube. The corresponding positions of the object are read by the micrometer, and a curve constructed with ordinates equal to these readings, and abscissas to the position of the middle of the bubble of the level. The reading of the micrometer corresponding to a perfectly level line must next be determined. This may be found by setting the telescope up at two not very distant points, and reading the height of each from the other. The mean will give the direction of a horizontal line; since the elevation in one case equals the depression in the other. The direction is, however, best found by observing the height of some known objects; since this eliminates various errors, as will be described below. The height of any object is more readily determined by directing the telescope towards it, and bringing the bubble nearly to the centre of the tube. Then read the position of the object by the micrometer; and, finally, read the exact position of the two ends of the bubble, taking care not to touch the telescope. These readings may then be reduced to seconds of altitude, as follows: Call A the required altitude in seconds, m the reading of the micrometer, m^1 its reading when the telescope is directed towards an object at the same height as its own, and b the mean of the two ends of the bubble of the level. Again, let s equal the magnitude of each division of the level in seconds, and l the corresponding magnitude of the level divisions. Then $A = (m - m^1)\ s + bl$. The elevation in metres or feet is then found by multiplying the tangent of this angle by the horizontal distance of the object, and correcting for the curvature of the earth and for refraction. The first of these corrections may be made with great precision by the formulas or table given in the Coast-Survey Report for 1871, pp. 160 and 169. The second correction is, however, very irregular, and may, therefore, generally be regarded as nearly proportional to the square of the distance. Since the correction for curvature is also nearly proportional to the square of the distance, we may write the elevation $E = D \operatorname{tang} A + m\,D^2$, in which D is the horizontal distance, and m a quantity dependent on the condition of the air. If, therefore, the height of any distant object visible is known, it is better to deduce *m* from its observed altitude, and from this compute the other elevations. Were it not for the uncertain error of refraction, this instrument would give results of extreme precision. Thus an error of 6″ in the altitude of a mountain one hundred kilometres distant would only correspond to a difference in height of about three metres. The uncertainty of refraction is much greater than this, and far exceeds the instrumental errors, except in a small telescope. Since, however, this cause of error is present when the theodolite is used, we see that altitudes can be obtained by this instrument with all the precision of the best theodolite; in fact, with all the accuracy of which the method is capable. Apart from its lightness and cheapness, it has this great advantage over a theodolite, — that, since the level is firmly attached to the telescope, there is little liability to error; while, as the theodolite measures the angle between the telescope and the horizontal limb of the instrument, any injury is liable to throw it out of adjustment. With the instrument as described above, no angles could be measured greater than the diameter of the field of view. This difficulty may be remedied by attaching another level, slightly inclined to the first, so that the two fields of view corresponding to a horizontal position of the two levels shall be nearly tangent to each other. A third level serves still further to extend the range of the instrument. Thus, if the field of view is about 2°, angles between 1° and — 1° may be measured by the first level, between 1° and 3° with the second, and between — 1° and — 3° with the third. The instrument, in this form, may be called a micrometer-level. One of its greatest advantages is the rapidity with which elevations may be measured. There is no difficulty in measuring thirty or forty mountains in this way per hour, without the labor of ascending them; while by the barometer it rarely happens that more than one can be measured in a day, and with the ordinary level the altitude of a high mountain would be the labor of days or weeks. The rapidity is also much greater than that of a theodolite; since no accurate mounting is needed, and a micrometer-scale can be read at least as quickly as the telescope can be set, so that the entire time of reading the circle by the vernier is saved.

One of the principal advantages of both the instruments here proposed is, that either may be made out of a telescope such as any explorer would be likely to carry. By simply adding a mirror in front, a photographed scale, and three levels, distances and elevations may be measured with all the accuracy ordinarily required. This method may be applied with especial advantage on a mountain-top;

since the elevations of all other mountains in sight, except those in the immediate vicinity, may be determined.

The fact is worth noting, that, even if the error from refraction could be eliminated, the method of zenith-distances would not equal in accuracy that of ordinary levelling. For suppose that the sights are taken at distances d, and that the probable error of each is e. If n sights are taken, or the distance travelled is nd, the probable error will be only $e\sqrt{n}$, since the positive and negative errors will probably in part neutralize. The error in the method of zenith-distances will, however, be proportional to the distance, or will be ne. Thus, if sights are taken every hundred metres with a probable error of 1 mm., the probable error of the level in ten kilometres will be 10 mms., since $n = 100$; while with zenith-distances the error would be 100 mms. Evidently, therefore, within reasonable limits, to attain the greatest accuracy with the level, the sights should be as short as possible, —.a fact in accordance with general experience.

Evidently the telescope of a theodolite may be converted into a micrometer level by inserting in its eye-piece a scale, and attaching three levels. Small vertical angles, which are those most used in surveying, can then be measured more accurately than by a vertical circle. In the same way, a similar attachment may be made to the telescope of a plane-table; and the advantage is especially marked in this case, since an accurate mounting is not needed. A further application may then be made; namely, to determine the distance when the height is known. Suppose that a distant pond is observed from the top of a hill. The telescope is directed to various portions of its shore, and the apparent depression observed. Since every portion must be at an equal distance below the observer, it is easily shown that the distance is always inversely proportional to the depression. Accordingly, if the direction of each part of the shore is marked on the plane-table sheet by a line, and a distance is laid off on this inversely as the observed depression, a map of the pond is quickly made. This may be reduced to its true scale if we know the position of any one point, or the height of the observer above the water. If the shore is abrupt or wooded, only the farther edge of the shore can be thus surveyed, or rather the portion where the actual shore-line is visible. This method is in fact a form of stadia, in which the measuring-pole is replaced by the constant vertical distance between the eye and the plane of the water. The same method may be used for determining the form of an island, of a coast-line, or of a river winding through a nearly level meadow. The form of a pond or island may also be obtained in the same way from a drawing made by a camera obscura or camera lucida, or from a photograph; and has the advantage that it begins to be accurate for depressions greater than 2° or 3° just where they pass out of the range of the micrometer-level as described above.

Valuable observations on the changes in the dip and in the refraction might be made with a large telescope of this form. It is much to be desired that such observations might be conducted for a period of years from two such stations as Mount Washington and Portland. As the pressure, temperature, and moisture of these points is already determined by the Signal-Service Department, a small additional expense would furnish a valuable addition to our knowledge of the atmospheric refraction.